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RPM-SIM: A Comparison of Simulated Versus Recorded Data

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RPM-SIM SIMULATOR: A COMPARISON OF SIMULATED VERSUS RECORDED DATA

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ABSTRACT

This paper compares simulated versus recorded data for the RPM-SIM simulator, developed at the National Renewable Energy Laboratory's National Wind Technology Center. The simulator was used to study the system dynamics of a wind/diesel hybrid power system. We also provide information on newly developed simulator modules that will be released. The simulator performed extremely well, demonstrating flexibility in making modifications and including specialized modules required for problem solving. We also outline several possible applications for this tool.

INTRODUCTION

Hybrid power systems combine continuously available diesel power with pollution-free wind and/or solar energy. Another advantage of these systems is that annual diesel fuel consumption can be reduced, thus minimizing pollution levels. However, to take full advantage of the wind and/or solar energy during periods of maximum availability, a proper control system has to be designed, subject to the constraints for a particular application. It has to maintain power quality measured by electrical performance (i.e., both the voltage and the frequency have to be properly controlled). Thus, each new system must be simulated to confirm that a particular control strategy results in desired system performance.

Using the VisSim™[†] visual environment, we developed the modular simulation system RPM-SIM[1-3] to facilitate a low-cost application-specific study of the system dynamics of wind-solar-diesel hybrid power systems. The simulation can aid developing system control strategies to balance the power flows under different generation and load conditions. Using the typical modules provided, it is easy to set up a particular system configuration. Some simulation studies require modifications of the existing modules and/or inclusion of specialized modules[4]. In the simulation study presented in this paper, we use the dump load module, which we modified to represent full physical model of the Wales Control System Dump Load Dispatch used at the Hybrid Power Test Bed (HPTB) located at the National Renewable Energy Laboratory.

Many researchers recognized the need for a tool that would facilitate analysis and design of hybrid power systems. An interesting study of modeling efforts of wind/diesel systems was performed by Jeffries.[5] Among those who have developed dynamic models of wind/diesel systems (in chronological order) are Tsitsovits and Freris,[6] Pierik and De Bonte,[7] Papadopulos et al.,[8] Uhlen and Skarstain,[9] Manwell et al.,[10] Papadopulos

[†] VisSim is the trademark of Visual Solutions.

et al.,[11] Lundsager et al.,[12] Binder,[13] Jeffries et al.,[14] and Ladakakos et al.[15]

Of the various simulation tools, our simulator includes probably the largest selection of modules and control strategies. For example, the user can model systems that contain a diesel generator and an inverter connected to a battery bank or to a photovoltaic (PV) array; the inverter can work in a slave mode or in a master mode when the diesel generator is idling. In such a system, the user can easily program the master/slave switching strategy. It is also possible to simulate systems without diesel generators (such as battery charging systems) with one or more wind turbine generators, in which the frequency and voltage are controlled by the inverter operating in the master mode. The RPM-SIM is the first dynamic hybrid system with a symbolic graphical user interface.

Figure 1 presents principal modules of the RPM-SIM included in a single-line diagram of a hybrid power system. All elements of the simulated system are connected to one module, called the point of common coupling (PCC). The other principal modules shown in Figure 1 are the diesel generator (DG), the alternating current (AC) wind turbine (WT) with the induction generator and the wind speed time series as the input, the rotary converter (RC) with the battery bank (BB), the inverter with the PV array, the village load (VL), and the dump load (DL). R+jX represents the transmission-line impedance and PFC represents the power-factor-correcting capacitors.

In all electrical simulations, we use the d-q axis convention and synchronous reference frame. In the PCC module, the q-axis and d-axis components v_{qs1} and v_{ds1} of the line voltage V_s are defined. In electric machine and power system analysis, it is common to use the transformation from three phase quantities a, b, and c into the d-q axis. This transformation, known as Park's transformation, was pioneered by Park[16] and Stanley.[17] In 1965, Krause and Thomas[18] generalized the d-q transformation for arbitrary reference frame. The Park's transformation has the unique property of eliminating all time-varying inductances from the voltage equations. It also is used by Ong[19] for dynamic simulation of electric machinary.

For all modules included in the simulator, we assumed (for both real and reactive power) the following general power sign convention: the power absorbed is displayed as negative and the power generated is displayed as positive. A village load (as an inductive load) always absorbs both the real and the reactive power and both powers are always negative. The real power of a diesel generator always remains positive and its reactive power may be positive or negative. The real power of the wind turbine generator is negative during motoring and is positive during generation. Its reactive power is always absorbed, i.e., it is displayed as a negative quantity. This power convention makes easy the interpretation of the simulation results. In particular, it makes apparent the interpretation of the instantaneous power balance.

In the sections that follow we first describe the modules of the simulator. We discuss some modifications done to account for unmeasured variables and/or to include the specifics of the simulated system. Next we present simulation results versus recorded data. Finally we summarize the results and present the potential applications of the simulator.

SIMULATOR MODULES

Diesel generator module

The diesel generator module, presented in Figure 2, includes models of the diesel engine and the synchronous generator, the engine speed control block, and the voltage regulator. The engine speed control block generates the fuel/air ratio, represented by the $\%_{FUEL}$ variable, to keep the frequency constant. The voltage regulator determines the field current of the synchronous generator necessary to keep the voltage constant under varying load conditions. The voltage set point V_{s_ref} and the frequency set point f_b can be easily set at required values by the user using the dialog boxes in the simulation diagram at the level shown in Figure 2.

With the addition of the first-order dynamics, we model the diesel engine according to the static relationship between the fuel/air ratio input and the generated power output. The aforementioned static characteristic is represented as a straight line with the dead zone. The slope of the straight line part, which represents diesel capacity, and the dead zone, which represents the minimum value of the fuel/air ratio, are to be chosen by the user to approximate the engine involved. In addition, the user can set the minimum diesel power P_{diesel_min} as a required percentage of the rated value. This variable is used by the dump load controller, which maintains this minimum diesel load. Thus, the dump load is active only when the diesel power is lower than the minimum diesel power.

Figure 3 presents the principle of the voltage and frequency control implemented by the RPM-SIM model of the diesel generator.

AC wind turbine module

The AC wind turbine module simulates two-step conversion of wind power to electrical power. In the first step, wind power is converted to mechanical power represented by the torque developed by the wind turbine rotor and transmitted through the gearbox to the induction generator. In the second step, electrical power is obtained from the induction generator connected to the line. The wind speed is represented in time series.

Figure 4 shows the principal functional blocks of the AC Wind Turbine module, together with their interconnections and all inputs and outputs. The reactive power has two components, one absorbed by the induction generator and the other contributed by the power factor correction capacitor block. The user can obtain its lower level expansion by clicking with the mouse on any of the blocks shown in Figure 4.

Dump load module

The dump load module is composed of parallel resistive loads. The principle purpose of the dump load is to keep the diesel-generated power above a user-prescribed fraction of its rated power. It can also (under special circumstances) be used to control the frequency. So, we have the following control strategies available:

- Diesel power control strategy.
- Frequency control strategy.

Either control strategy dynamically determines the number of the dump load elements to be connected in parallel.

Village load module

The village load (VL) module generates the i_{qV} and i_{dV} components of the load current. The user declares the rated real power consumption P_v and the power factor pf and has a choice between fixed load (for which he/she provides the constant values of P_{v1} and pf_1)and the load profile (for which he/she provides the time series of P_{v2} and pf_2). The user makes his/her choice by clicking the button in the parameter module of the VL. The RPM-SIM format of a village load profile is shown in Figure 5.

Rotary converter/battery bank assembly

Figure 6 shows, that the rotary converter/battery bank assembly consists of a battery bank and two machines: (1) a DC machine and (2) a synchronous machine. Figure 6 shows the principal functional modules of the rotary converter, together with their connections and all inputs and outputs.

The rotary converter/battery bank assembly can be set up to operate in the synchronous condenser mode, i.e., to provide or absorb reactive power. This is accomplished by setting to zero the battery reference power and consequently maintaining zero shaft torque and zero real power output.

Other RPM-SIM modules to be included in the second release of the simulator

In this section, we briefly present the RPM-SIM modules, which have not been included in the simulation performed to present the model performance versus recorded data. These include the Inverter Module and the PV Array Module.

The inverters can work in one of two modes, i.e., the master mode or the slave mode. In the master mode, the inverter controls the system's frequency and voltage. The power exchange is determined by the system's power balance. In the slave mode, the real and reactive power required to be generated or to be absorbed are specified by the user.

The transfer from slave mode to master mode is determined based on the control strategy designed by the hybrid power plant designer or operator. This is suitable, for example, when the inverter uses a sufficient battery storage site, and during nighttime operation when the inverter's battery carries the load and the diesel generator is turned off. Power generated by occasional wind during the night will be stored in the battery. During the day, when the load is close to rated power, the diesel is turned on and the inverter is operated in the slave mode to charge the battery and to support occasional peak loads.

We developed a model of the inverter, which makes possible all specified options of operation. We tested this model under variable load conditions, switching between the slave mode, in which the system's voltage and frequency are controlled by the diesel generator, and the master mode, in which the diesel generator is disconnected and the voltage and frequency control is taken over by the inverter. In addition, we tested the inverter's operation in conjunction with the battery and the PV array.

The PV arrays are commercially available in modules. The PV modules are used to build an array and their I-V characteristics are considered as I-V characteristics of the elementary PV array unit. In our model, we introduced a single solar cell as this elementary unit. Consequently, when setting up the simulation with commercial PV arrays, the user must declare N_{ser} as a number of modules in one row or connected in series, and N_{par} as a number of module rows connected in parallel.

The representation of a cell for varying insolation and temperature is accomplished by the scaling coefficients K_v and K_i, which are functions of the insolation and temperature specified by the files K_v.map and K_i.map, respectively. These functions are represented at several points in a two-dimensional table. The values of K_v and K_i for temperature and isolation values not included in the table are determined by interpolation and extrapolation.

The I-V characteristics for a number of the commercial PV modules under adjustable environmental parameters such as temperature, beam irradiance, diffuse irradiance, wind speed, site altitude, sun elevation, angle of incidence and others along with manufacturer's parameters of the module can be obtained using Sandia National Laboratories' IVTracer Program. These data (for a particular solar module involved in the simulated system) can be used to generate the files K_v.map and K_i.map.

In addition, we developed the PV Array-Inverter Assembly, which converts the direct current (DC) power generated by the PV array to AC power.

COMPARISON OF SIMULATED VERSUS RECORDED DATA

In this study, we use the data recorded from the Hybrid Power System Test Bed (HPTB) located at the National Renewable Energy Laboratory. The power system included: the diesel generator, the AOC wind turbine, the dump load (DL), and the village load (VL). The arrangement of the test bed is illustrated in Figure 7. The recorded time series sets include the real and reactive power of each device, the line voltage, and the frequency. The data were recorded over 10-second intervals with a sampling period of 0.001second. Because the wind speed was not measured, we could only compare simulated versus recorded data using two simulation runs:

(a) Generating the simulated data for the system with the standard models of the diesel generator and the village load, and the models of the other system modules modified to conform to the recorded power files.

(b) Generating the simulated data for the same system as in (a), but with the full physical model of the Wales Control System Dump Load Dispatch used at the HPTB when the recorded data was acquired.

We performed simulations for five sets of data for the same system run under different conditions. However, we discuss the results for only one of these sets and two simulation runs: using a simplified and a full physical model of the dump load.

The wind turbine recorded data consisted of the real and reactive power files, P_{WT} and Q_{WT}, respectively (i.e., the wind speed was not measured). Consequently, we had to modify our wind turbine generator model. Using these data and the reference voltage, we calculated the equivalent resistance and inductance. Then, using the real voltage generated in the simulation, we calculated the equivalent d and q current components contributed by the wind turbine generator at the point of common coupling (PCC). In addition, using these currents and the q and d components of the voltage generated in the simulation, we calculated the wind turbine real and reactive power. This simulation approach is shown in the block diagram in Figure 8.

In the first run of the simulation, we included the modified dump load block, for which we calculated the power absorbed using the recorded power file and the voltage generated in the simulated system.

For the second simulation run, we used the same data but did not use the dump load power file. Instead, we included the model of the real dump load block with the Wales Control System Dump Load Dispatch used at the HPTB. The dump load at the HPTB has 20 elements of 10 kW each. The Wales Control System Programmable Logic Controller (PLC) dispatches dump load elements in order to maintain a minimum load for the diesel generator. The algorithm uses a modified Proportional+Integral+Derivative (PID) loop to determine the dump load kW required. It subtracts the current value of the dump load to determine the delta dump load power required, and divides this value by the dump load step size and rounds to determine the number of dump load elements to add or remove.[1]

The recorded village load data consisted of the real and reactive power files P_v and Q_v, respectively. Therefore, the corresponding power factor *pf* was first determined and then the standard option of the village load profile data was used.

The simulated power, voltage, and frequency traces closely follow those recorded after 2 seconds approximately, which is the start-up time of the diesel generator in the simulation. This is the time needed for the voltage level at the synchronous generator to reach the reference. At time zero, the initial condition of the field current is zero. We only present the representative results. In both cases (see Figures 9 and 10), the dark line is used for simulated traces and the light line is used for recorded traces. The results of comparison run (a) (with the standard diesel generator model) are represented in Figure 9 by the recorded and simulated traces for one of the data sets. We also combined as one variable the real power consumed by the village and the dump load. Considering a slight oscillatory power imbalance in the recorded data (shown in Figure 9) and the smoothing involved in the measuring system, there is a very good agreement (within 2%-5%) between the recorded and simulated traces.

The results for the comparison run (b) (with the physical model of the dump load) and the same recorded data are shown in Figure 10. We separated the power traces for the village load and the dump load. We do not again illustrate the power imbalance of the data recorded. A good agreement (within 2-5%) can also be observed in this case.

CONCLUSIONS

In this paper, we compared RPM-SIM Simulator data versus the data recorded at the Hybrid Power System Test Bed (HPTB) at the National Wind Technology

Center, NREL. We developed the modular simulation system in order to

- Study applications and cost-effective performance of wind-diesel hybrid power systems. (Both mechanical and electrical components are simulated.)
- Analyze both static and dynamic performance.
- Develop control strategies.
- Simulate different wind speed and village load profiles.

The system has the following capabilities and/or characteristics:

- Modular and multilevel structure is provided by the VisSim visual environment.
- System presentation is clear and easy to understand.
- Customized configuration setup is within a click of the mouse.
- Modifications are easy to make.
- Effects of system modifications can be immediately examined.

This simulation tool can be used for:

- **Control strategy simulation**
  A proper control strategy must be developed to take full advantage of the available wind energy and to minimize diesel fuel consumption, while maintaining desired system performance.
- **Inclusion of constraints**
  To implement this control strategy, a control system must be designed subject to the constraints for a particular application. These include the power generation limitations of the diesel generator, wind turbine generator, and battery bank/rotary converter assembly, excitation time constants, and dump load parameters.
- **Checking stability of the power system under time-varying conditions**
  To properly control the system's voltage and frequency, the time-varying power generation/consumption conditions of the system must be considered. The levels of changes that drive the system into instability should be determined. The three factors to be considered are:
  (1) Wind speed: High winds may drive the diesel engine and cause loss of frequency control and instability.
  (2) Village load (represented by the real power and the power factor): This includes events such as start-up of induction motor load, start-up of large heating load, loss of load, and sudden change of power factor.
  (3) Minimum diesel load: To maintain system stability diesel generation must be kept at the required minimum level by a proper control strategy of the dump load.

These are just a few of the possible uses of the RPM-SIM. However, because of its flexibility and modularity, it can, if necessary, be easily extended to meet any need that might emerge in the design of an autonomous power system with renewable energy sources. Thus, if some specialized modules for a particular simulation are needed, the user can easily include them. The RPM-SIM simulator can be obtained by contacting NREL.

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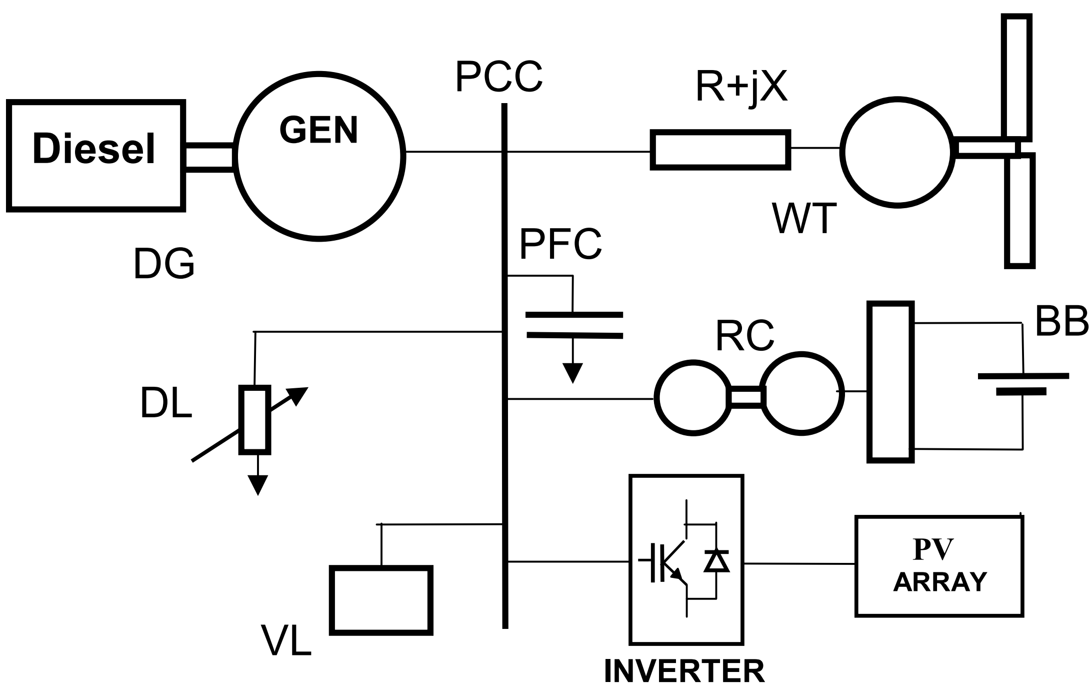


Figure 1. Principal modules of the RPM-SIM included in a single-line diagram of a hybrid power system.

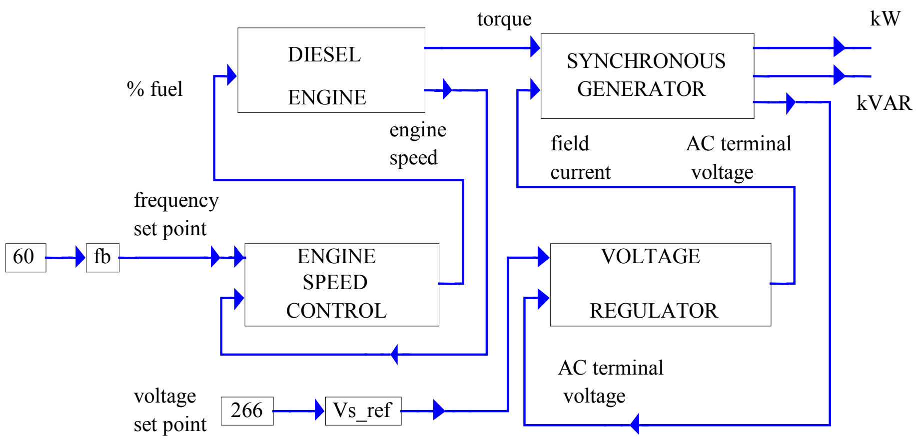


Figure 2. Block diagram of the DG module.

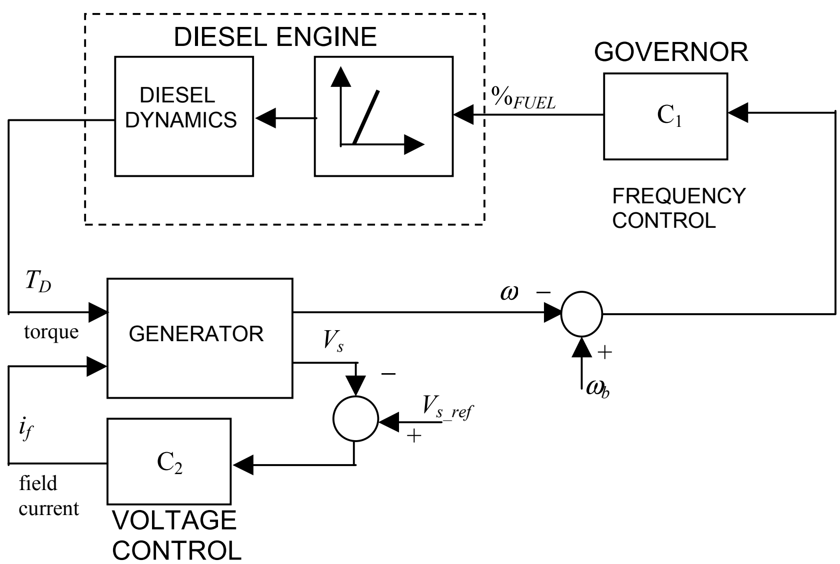


Figure 3. The principle of voltage and frequency control.

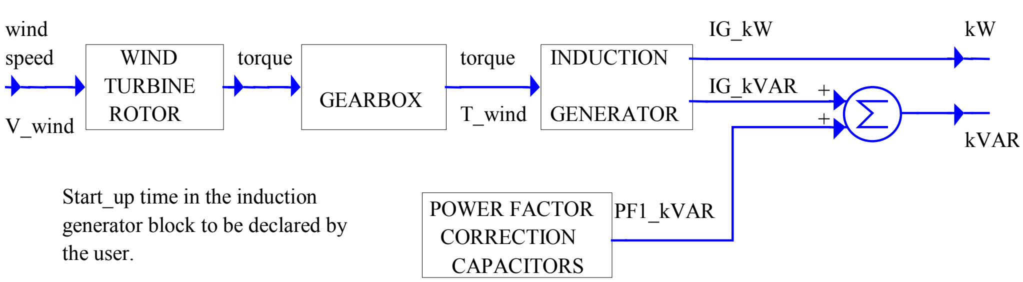
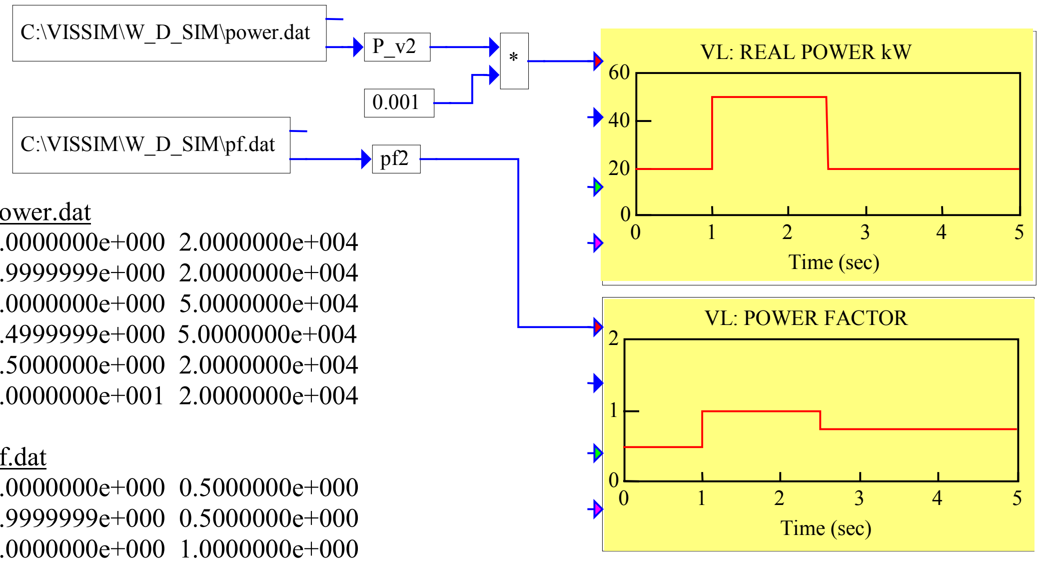


Figure 4. Simulation diagram of the wind turbine generator.



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0.9999999e+000 2.0000000e+004
1.0000000e+000 5.0000000e+004
2.4999999e+000 5.0000000e+004
2.5000000e+000 2.0000000e+004
2.0000000e+001 2.0000000e+004

pf.dat
0.0000000e+000 0.5000000e+000
0.9999999e+000 0.5000000e+000
1.0000000e+000 1.0000000e+000
2.4999999e+000 1.0000000e+000
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Figure 5. An example of a village load profile represented graphically and by ASCII data files power.dat and pf.dat.

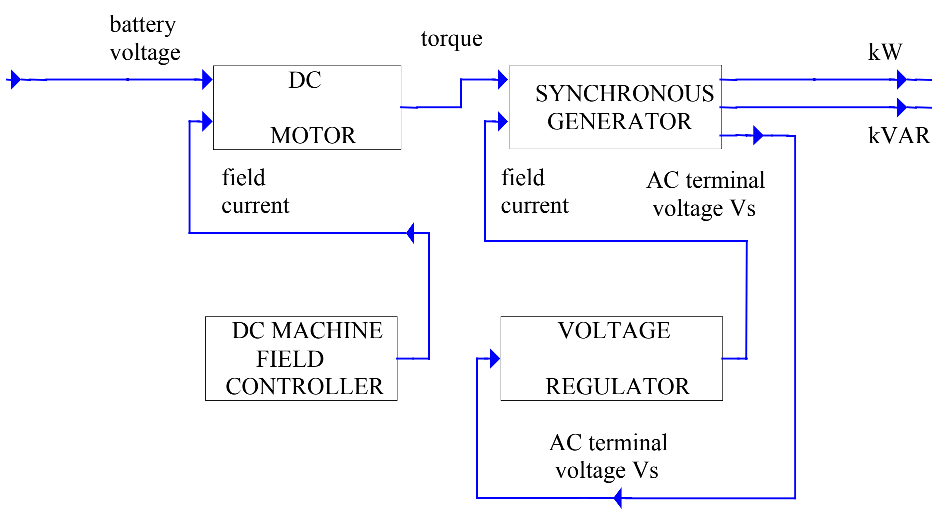

Figure 6. Principal functional blocks of the rotary converter.

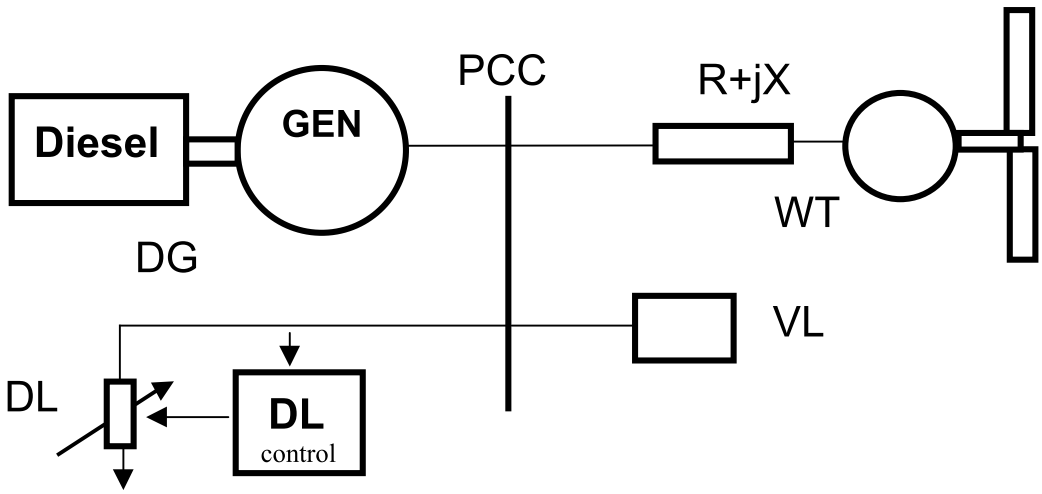

Figure 7. Connection diagram for the system tested at the HPTB.

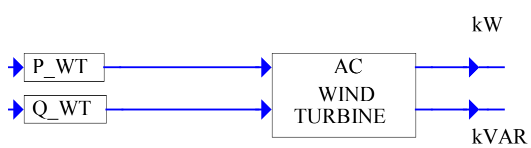

Figure 8. Symbolic representation of the wind turbine generator model with real and reactive power file as the input.

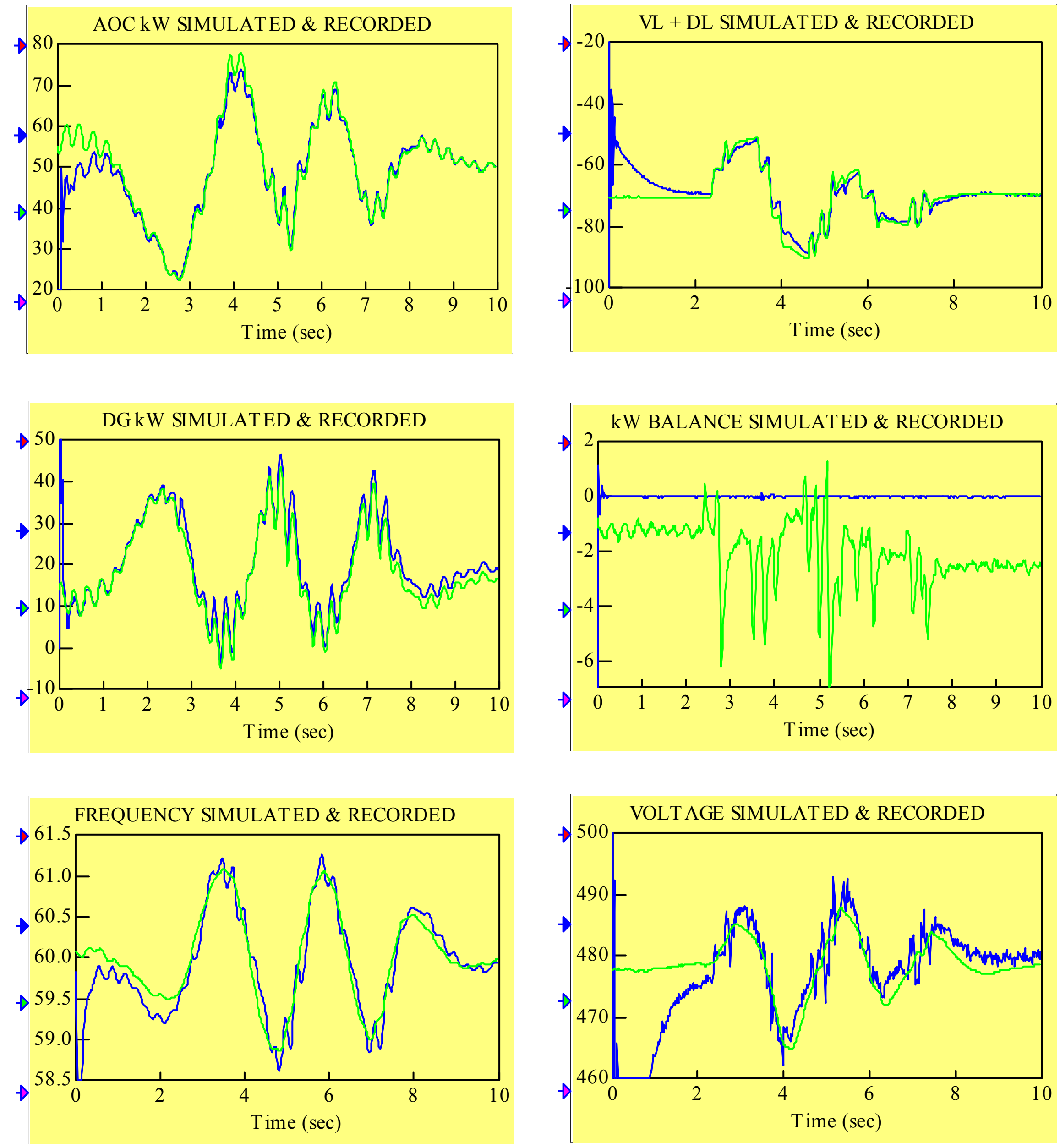

Figure 9. Simulation results for the run (a): the dark line is used for traces simulated and the light line is used for traces recorded.

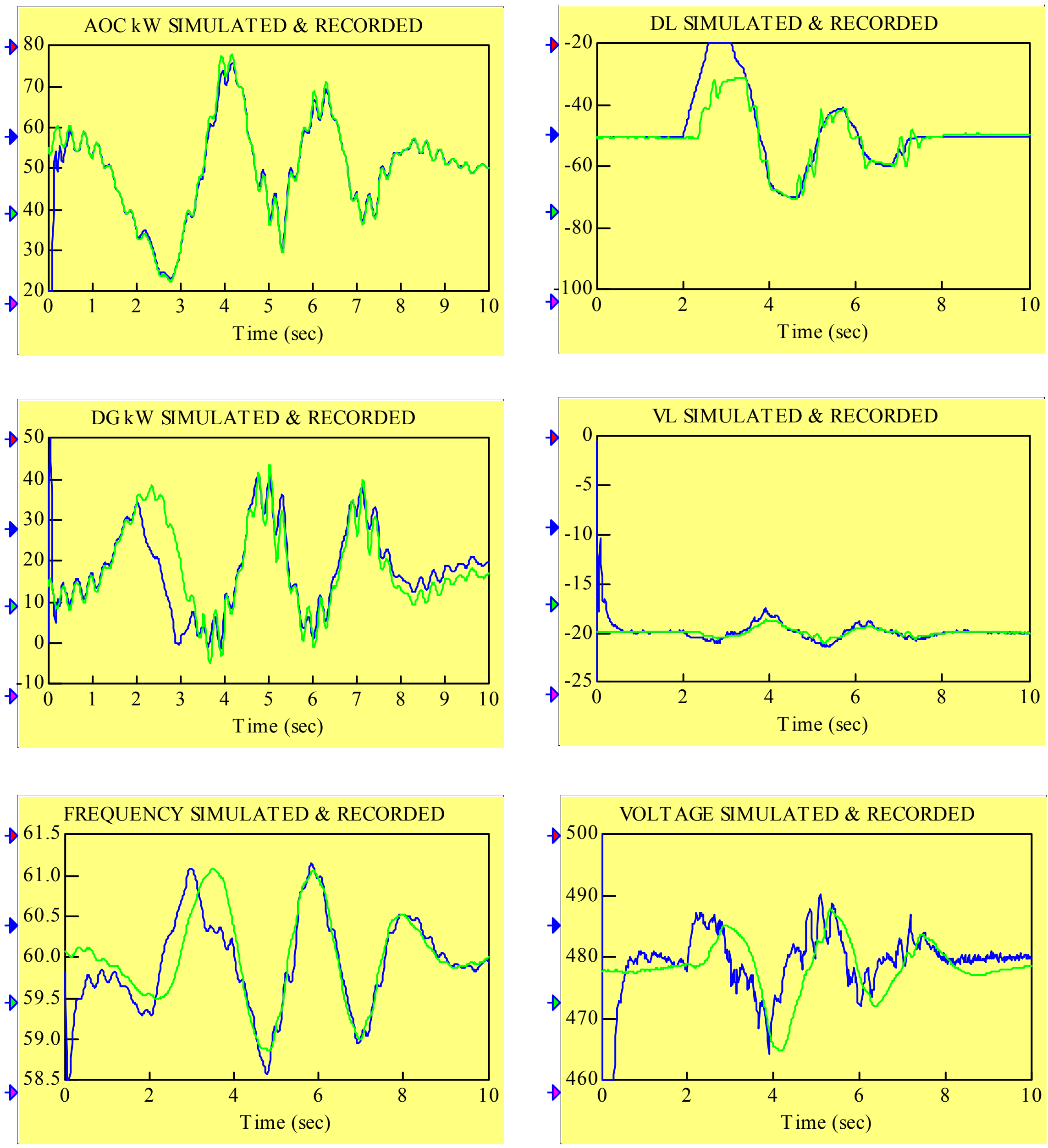

Figure 10. Simulation results for the run (b): the dark line is used for traces simulated and the light line is used for traces recorded.

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